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SPECTROSCOPIC STUDY OF A MAGNETICALLY  
CONFINED NITROGEN PLASMA COLUMN

by

Joseph Robert Cote



# United States Naval Postgraduate School



## THESIS

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CONFINED NITROGEN PLASMA COLUMN

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June 1969

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Spectroscopic Study of a Magnetically  
Confined Nitrogen Plasma Column

by

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## ABSTRACT

The Plasma Spectrophotometer constructed at the Naval Postgraduate School in 1968 was modified by the addition of a photomultiplier cooling device to improve time resolution and increase the accuracy of the computed values of the relative intensities of the nitrogen spectrum in the magnetically confined nitrogen plasma column.

The relative intensities determined were used to analyze the variation in local electron temperature of the singly and doubly ionized nitrogen atoms with respect to magnetic field. The local electron temperature was found to vary with increasing magnetic field, reaching a peak temperature of 8.1 electron volts at 4200 gauss.

Evaluation of the relative number densities of the two ionic species indicated that the local electron temperature of the column was the local electron temperature of the singly ionized nitrogen atom.

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Deepest appreciation goes to my wife Anita, who has supported my efforts positively over the past two years.

## I. INTRODUCTION

This investigation is a continuation of the analyses of the characteristics of the highly ionized plasma column produced at the Naval Postgraduate School Plasma Facility which have been undertaken since its fabrication in 1962. The principle objective of this study was the analysis of shock waves in the magnetically confined plasma column by means of the dual-Ebert type spectrophotometer constructed at the Plasma Facility in 1968 by Orlicki [1]. The spectrophotometer was to be modified to improve time and spatial resolution and then used to determine the variation of electron temperatures and relative number densities of key ionic species with changes in the machine parameters, such as magnetic field.

The key ionic species of the unperturbed plasma were identified as the singly and doubly ionized atom ( $N^+$  and  $N^{++}$ ) and the singly ionized molecule ( $N_2^+$ ) [1]. These species are the basis of the continued study. The identified lines are listed in Table I.

Table I. Identified Lines of the Nitrogen Plasma

$N^+$ Wavelength ( $\overset{O}{A}$ )	$N^{++}$ Wavelength ( $\overset{O}{A}$ )
4124.100	4097.309
4133.654	4103.370
4145.759	4200.000
4601.490	4514.900
4607.166	4518.200
4613.887	4535.100
4621.405	
4643.106	

A complete reanalysis of the plasma in the unperturbed state had to be accomplished first because of several modifications to the Plasma Facility, including the addition of a ten inch diffusion pump to the cathode end of the system. Thus the local electron temperature and the relative number densities of the two known nitrogen atom species and their variance with respect to changes in the magnetic field were to be determined to identify changes brought about through incorporation of the modifications.

## II. BACKGROUND

### A. SPECTROSCOPIC DIAGNOSTICS

The nitrogen plasma produced at the Naval Postgraduate School Plasma Facility emits sufficient light for spectroscopic observation and is also sufficiently dense and long-lived so that the assumption can be made that the velocity of the electrons is very nearly Maxwellian at any instant of time and at any point in space. The local electron temperature can then be treated as a function of time. Since electron impacts dominate almost all collisional rate processes, the local electron temperature is essentially the quantity determined in spectroscopic temperature measurements.

The electron density is usually involved in the relations used to calculate the electron temperature from observed intensities, and therefore temperature and density measurements are not really independent. An attempt to find a self-consistent solution of the various relationships between the directly measured spectroscopic quantities and densities and temperatures was made in this investigation.

Since the assumption that the plasma is in local thermal equilibrium (LTE) has been made, the relationship based on the fact that densities in various excited states are proportional to the products of the statistical weights with the exponentials of the negative ratios of excitation energy and the thermal energy  $kT$  may be used [2].

Quantitatively,

$$kT = \frac{E' - E}{\ln(I\lambda^3 g'f' / I'\lambda'^3 gf)}$$

where the quantities are defined as follows:



1. First Reference Line

$I$  = relative intensity

$\lambda$  = wavelength in meters

$g$  = statistical weight of the lower state ( $2J + 1$ )

$f$  = absorption oscillator strength

$E$  = excitation potential in joules

2. Second Reference Line -- same as above except designated by prime.

Excitation potentials and wavelengths may be obtained from the multiplet tables of Moore (1959) [3], or Striganov and Sventitski (1968) [4]. Precise wavelengths and statistical weights can be found in almost all cases, but this is not true of absorption oscillator strengths. Except for one-electron systems, the oscillator strengths given in the literature are approximate, with estimated errors ranging from 10 percent in the case of neutral and other relatively simple spectra to uncertainties of factors of two or three for more complex spectra [2,5].

Relative intensities can be measured with an accuracy of better than 10 percent, unless the wavelength separation of the lines is very large. Errors due to uncertainties in the oscillator strengths are usually the greatest source of error, and uncertainties of 30 percent in the argument of the logarithm are not uncommon. The uncertainty above is reflected in a similar temperature error, and since  $kT$  is usually of the order of the largest separation between excitation energies of non resonance lines, one can hardly improve accuracy by using resonance lines. The gain in separation between excitation energies is generally offset by larger errors in oscillator strengths, in relative intensity measurements, and with difficulties with self absorption [2,6].

Applying the concept of relative intensity to different ionic species to the equation for absolute intensity of a spectral line given by



Robinson and Lenn [6], and using the electron temperature determined from the equation on page 11, one can arrive at the relative density equation:

$$\frac{N_1}{N_2} = \frac{I_1 g_2 f_2}{I_2 g_1 f_1} \left( \frac{\lambda_1}{\lambda_2} \right)^3 e^{-(E_2 - E_1)/kT}$$

where the quantities are as defined earlier, except that they are now for two different species. Uncertainties from the only approximate validity of these equilibrium relations, from experimental errors, and also from errors in oscillator strengths, as mentioned above, are frequently of similar magnitude which implies that even with utmost care it is often not possible to reduce errors in relative densities below 30 percent.

It must be emphasized that several important criteria are applicable when using the above equations. These expressions are only applicable when the arc pressure is held constant [2], and certain ratios of parameters in both equations must be limited if meaningful results are to be obtained [2,6,7]. The intensity ratio must be on the order of 1.0 to 6.0, the difference in excitation potentials must be greater than 3.0 volts, and the wavelength separation of the lines must be small.

It has been assumed that the electron density is sufficient to maintain a Maxwellian Distribution of quantum state population, and if this is not so, and radiative depopulation of lower energy states takes place to any significant degree, then the population of states having energies above  $kT$  would be favored and the excitation temperature indicated by the line intensities would be higher than the actual electron temperatures [2].

## B. THE NITROGEN ATOM

The nitrogen atom has seven identified ionization states. However, for this investigation, only the singly and doubly ionized states are of concern. Their ionization potentials are 29.593 and 47.426 electron volts respectively [8]. The lines which were chosen to study are listed in Table II along with their relative intensities and transitions. All of the transitions listed are allowed [3,4]. Four lines of the singly ionized and three lines of the doubly ionized atoms, all marked by asterisk (\*), are listed among the more intense lines known in the nitrogen spectrum [4].

Table II. Relative Intensities and Transitions of Applicable Nitrogen Lines

	Wavelength ( $\text{\AA}$ )	I	Transition
N+			
	4124.100	4	$3s^5P - 3p^5S^0$
	4133.654	5	"
	4145.759	6	"
	*4601.490	11	$3s^3P^0 - 3p^3P$
	*4607.166	10	"
	4613.887	9	"
	*4621.405	10	"
	*4643.106	11	"
N++			
	*4097.310	10	$3s^2S - 3p^2P^0$
	*4103.370	9	"
	4200.00	6	$3s^2P^0 - 3p^2D$
	*4514.900	7	$3s^4P^0 - 3p^4D$
	4518.200	3	"
	4535.100	2	$3p^4S - 3d^4P^0$

The state of ionization in the plasma is due to many factors. The primary factor is the cathode current interaction which supplies energy

to thermionically emit electrons which collide with the gas column. The higher the cathode current, the greater number of electrons emitted and consequently, the greater the number of collisions the greater the energy exchange. The electrons removed in the ionization process may recollide with the cathode and cause secondary emissions which are capable of causing further ionizations. The cathode-anode accelerating potential makes further energy available to the thermionically emitted electrons, and so it continues. Other ionizations may occur within the plasma due to atomic, molecular or electron interactions which would be functions of other machine parameters such as magnetic field.

### C. THE PLASMA FACILITY

The experiment is carried out in the steady state plasma column, with plasma density of the order of  $10^{13} \text{ cm}^{-3}$ , provided by a hollow cathode reflex arc. This plasma is confined in a ten-foot long column along the axis of a six coil solenoid which produces a magnetic field of up to 10,000 gauss and is homogeneous to within 2.5% along the axis of the plasma column.

The plasma tube is a ten foot long series of four inch diameter pyrex sections with two access ports available on each side. The "theta" pinch section is located approximately thirty inches from the floating anode, and the access port used for the collection of spectroscopic data is 62 inches from the cathode (Figures 1 & 2).

The magnetic field is provided by six main magnet coils, a cathode magnet, a first anode magnet, and a mirror magnet at the floating end. All magnets are mounted coaxially to the tube and all are individually variable.

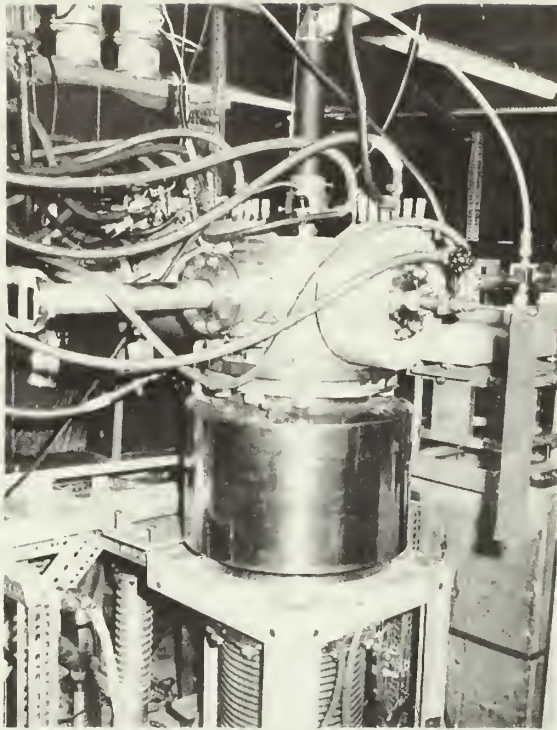


Figure 1  
Plasma Facility - End View, Cathode

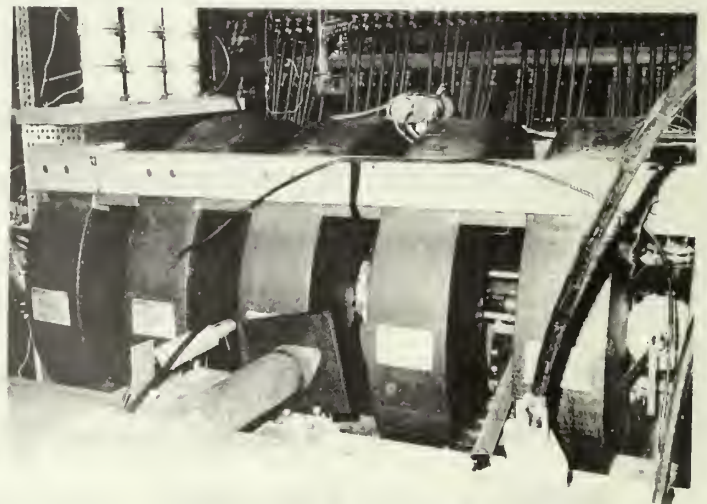


Figure 2  
Plasma Facility - Side View



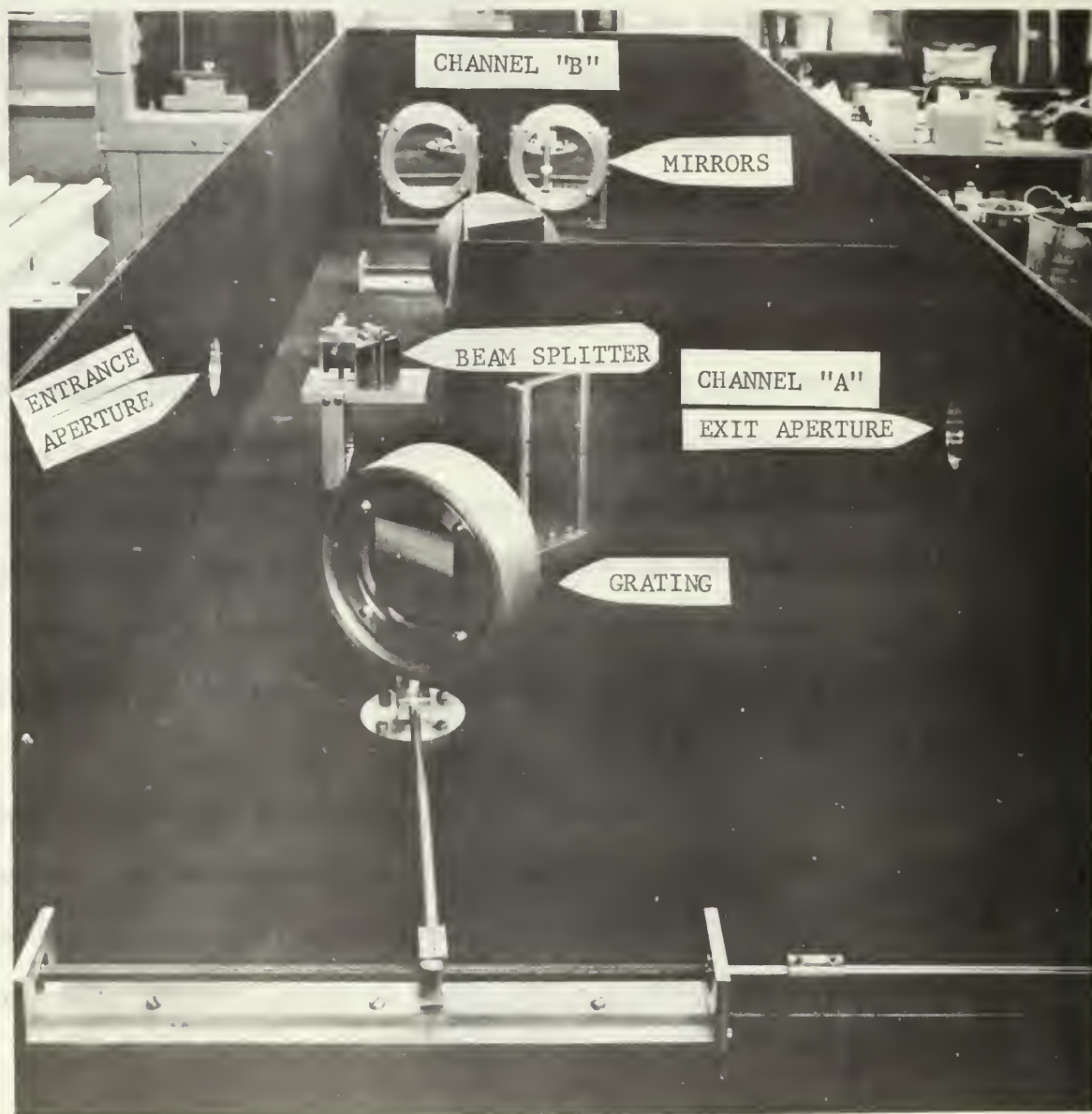
The nitrogen gas enters the tube at the cathode and flows through several centimeters of the cathode tube of tantalum where it is ionized by the high current discharge which runs into the interior of the tube. This highly ionized gas then leaves the cathode and forms the beam. The cathode is self heated and thus electrons are thermionically emitted from its inside walls or by field emission across a very thin sheath. Electrons which collide with gas molecules before returning to the walls are trapped and drawn out of the cathode by the axial potential gradient of the arc as well as by the pressure gradient of the plasma. The collisions of the electrons with the gas molecules produce positive ions and electrons, radiation, and possibly some metastable excited atoms. Nearly all of these products are trapped in the tube and return to the wall. This heats the wall to temperatures around  $3000^{\circ}\text{C}$ , and results in thermionic emission of electrons [9]. The cathode is heated locally to high temperatures and when cathode current is held to 60 amperes, the cathode life is around ten hours. The duration of the plasma column in a steady state was from a minimum of a few minutes to as long as four hours.

Argon is used to establish the initial plasma column, and, when it has stabilized, the system is switched over to nitrogen and the argon is turned off. The transition is readily observable in the column as it smoothly turns from blue to pink. Data is taken when the nitrogen beam is established.

#### D. PLASMA SPECTROPHOTOMETER

The plasma spectrophotometer is a dual-ebert type photoelectric spectrometer. It was designed to accept a beam of light through a single input slit, set at 300 microns, split that beam in half by means

Figure 3  
Internal View of Plasma Spectrophotometer



of a beam splitter, and pass the resultant beams to plane gratings which diffract the beams, after which they are focussed by spherical mirrors into two independent chambers [1]. (See Figure 3.) The diffracted beams exit through separate slits and are picked up by an Eldorado Differential Photometer Unit and recorded. The Eldorado is used because it contains all the apparatus necessary to perform this experiment, and is highly accurate, giving a high degree of spectroscopic resolution. It provides the photomultiplier heads, power supply and recording apparatus, and is also capable of mounting both end window and side window photomultiplier tubes.

The 1P21 photomultiplier tube was used for this experiment as it was the most suitable for the nitrogen lines under investigation. It is a side window tube with maximum sensitivity at  $4000 \text{ \AA}$  and with overall sensitivity from  $3100\text{--}5400 \text{ \AA}$ . At 1024 volts supply voltage, this tube gives a current amplification of  $2 \times 10^6$  with an equivalent noise level of only  $6 \times 10^{-12}$  lumens. Two other tubes are available, the 6903, head-on tube, which has a maximum sensitivity at  $4000 \text{ \AA}$  and overall sensitivity from  $2000\text{--}5600 \text{ \AA}$ , and the 7102, also a head-on tube, with a maximum response sensitivity at  $8000 \text{ \AA}$  and overall sensitivity between  $5600$  and  $9600 \text{ \AA}$ . The 6903 has a current amplification of  $4 \times 10^5$  and an equivalent noise level of  $6.7 \times 10^{-12}$  lumen. It is better suited for work in the ultraviolet region. The 7102 has a current amplification of  $4.6 \times 10^5$  and an equivalent noise level of  $7.5 \times 10^{-10}$  lumens, and is better suited for work in the near infra red region [10]. Using any or all of the aforementioned tubes gives the capability of covering the entire spectrum of the spectrometer,  $2000\text{--}9600 \text{ \AA}$ .

Setting the required wavelengths is accomplished through the use of digital counters capable of locating each individual setting. There is  $1/10 \text{ \AA}$  between successive settings. The gratings are mounted on an expanding lever-arm screw type mechanism which turns the grating and the digital counter at the same time. Settings can be made and accurately reproduced based on a prepared calibration curve (Figure 4). This curve was rechecked with a mercury arc lamp, after all modifications were applied, and no changes were found.



PLASMA SPECTROPHOTOMETER  
WAVELENGTH CALIBRATION CURVE (1)

(Number of Turns  
vs. Wavelength)

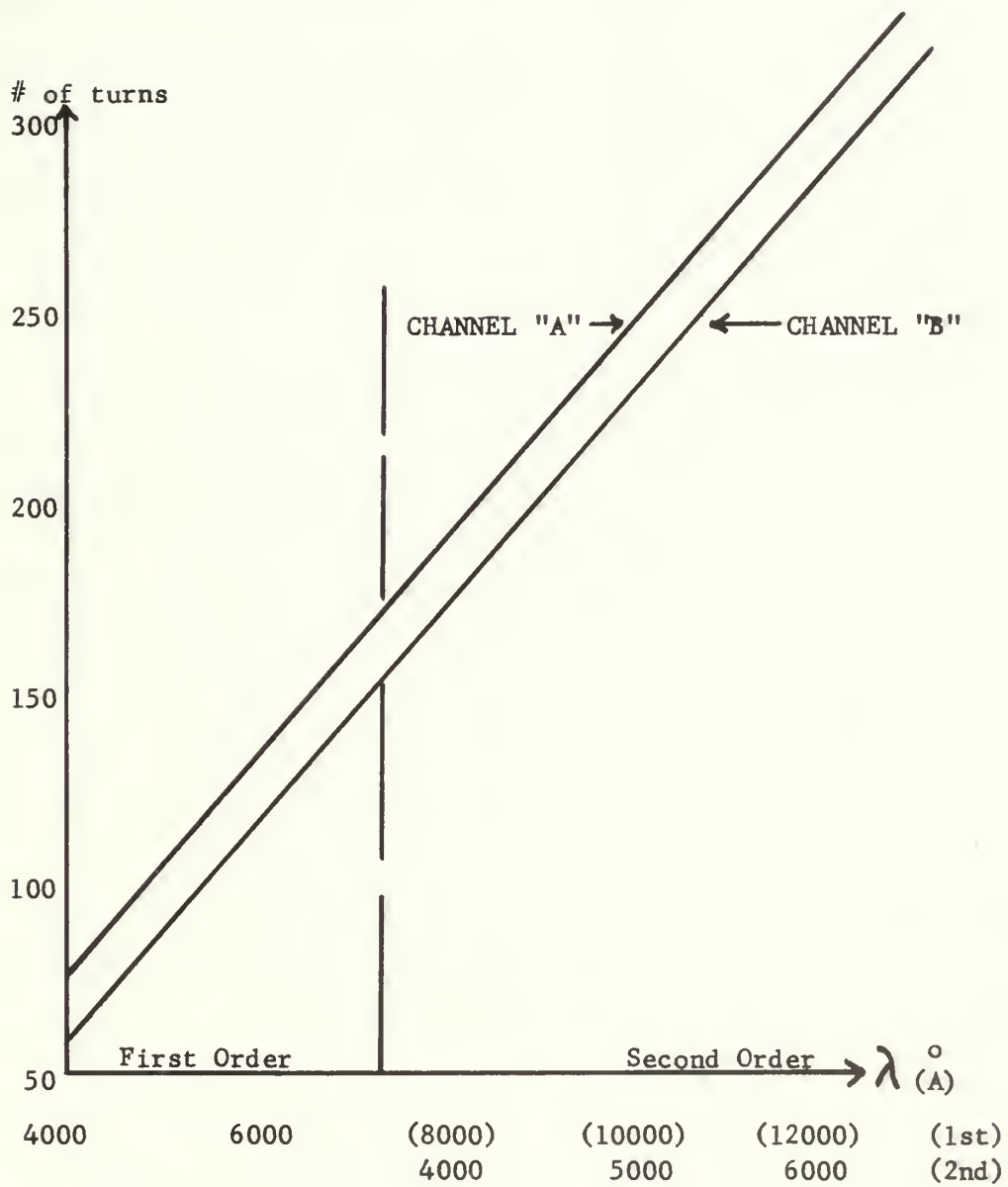


Figure 4

### III. EXPERIMENTAL PROCEDURES

#### A. MODIFICATIONS TO SPECTROPHOTOMETER

Since time resolution was desired, it was necessary to modify the differential photometer unit through the addition of a photomultiplier cooling system. The cooling of the photomultiplier tubes was necessary to reduce the detrimental effects of dark current and external noise [11,12]. A cooling device was constructed which reduced the dark current and external noise pickup rapidly and conveniently through the use of liquid nitrogen. No difficulty was experienced with electrical short circuits, but the usual problem of window fogging had to be resolved.

A schematic drawing of the cooling device is seen in Figure 5. The side window photomultiplier tube housing from the Eldorado unit was wrapped with a coil of copper tubing ending in the exit lens housing. The original aluminum lens housing was replaced with a nonconducting material, polyvinylchloride tubing (PVC), which had the proper internal dimensions and was machinable. A gas vent tube was installed in the top of the PVC tubing to prevent pressure buildup inside the system, and to allow water vapor to escape. The entire copper coil was connected to the tube housing with Thermon, Heat Transfer Cement [13]. Since the tube housing was aluminum, welding or brazing was impractical, and the heat transfer cement insured effective heat conduction between the metals. The entire system was then covered with polystyrene for further insulation.

In operation, liquid nitrogen is placed in a reservoir connected by a Tee device to the input end of both coils. The liquid nitrogen fills the coils to the height of the liquid in the reservoir and then begins

Side View of  
Spectrophotometer Cooling Device

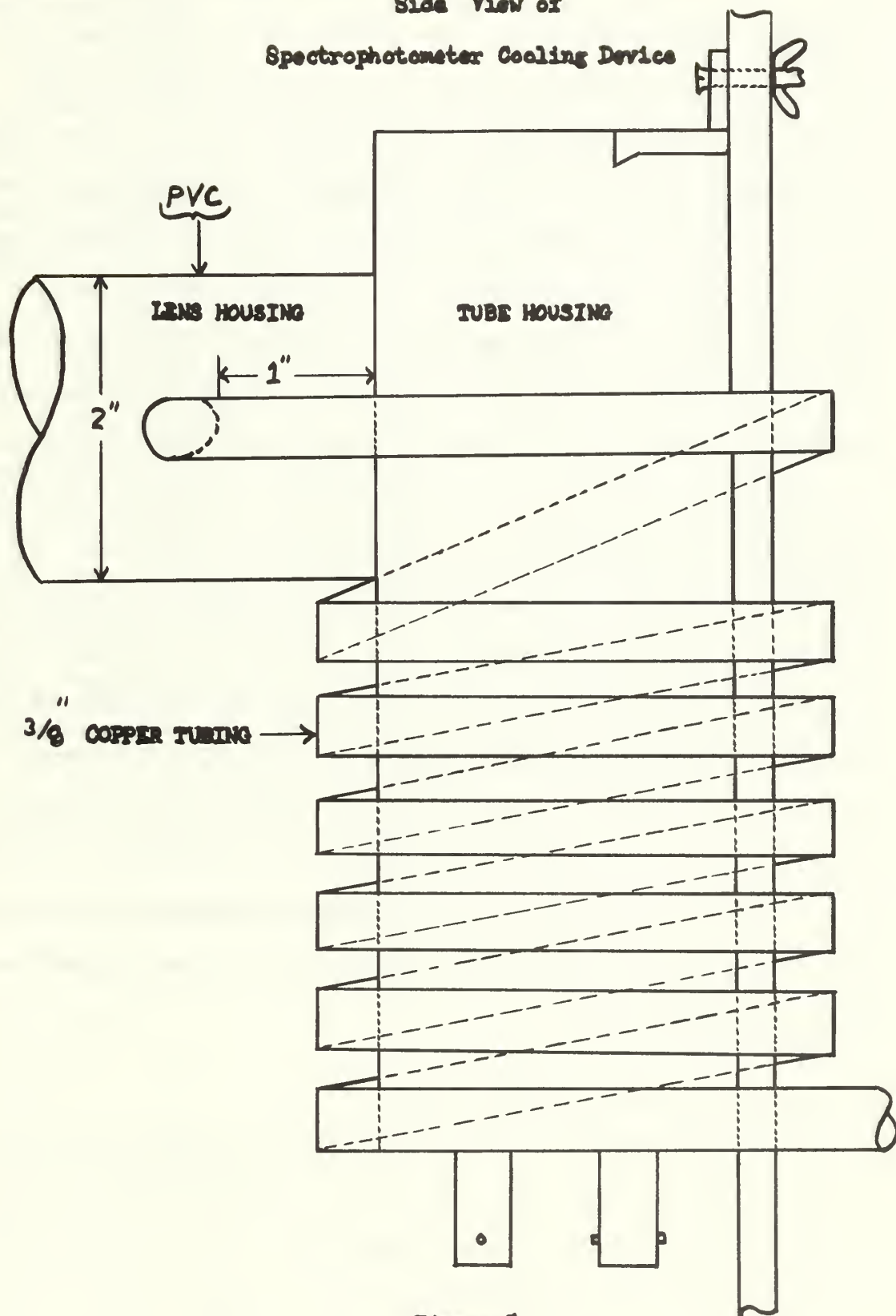


Figure 5

evaporating. Immediate cooling of the tube housing takes place through conduction. Because the walls of the housing cool first, water vapor that is present condenses upon them, thus preventing harmful condensation on the tube or its wiring. The nitrogen gas flows upward through the coil and fills the lens housing, cooling the photomultiplier tube and the lens. Excess gas escapes through the vent tube. To prevent fogging, a 1/16 inch coil of nichrome wire, six inches long, and wrapped in a fiberglass sheath to prevent radiation, was wrapped around the circumference of each lens, and connected to a variac. Adjustment of the variac as needed produces sufficient heating of the lens to prevent fogging.

Thermocouples inserted in the base of each photomultiplier tube housing register the temperature of the resistor bank of each tube. The photomultiplier tubes are cooled sufficiently for use fifteen or twenty minutes after filling with liquid nitrogen. About two liters of liquid nitrogen is needed to cool the tubes to about  $-80^{\circ}\text{C}$ , and about 1/4 liter of liquid nitrogen should be added each 10 minutes for a thirty minute period. Data can be taken for about 30 minutes after this without further cooling. The dark current, with 1012 volts across the tube, is reduced by a factor of about  $10^3$  within 20 minutes of applying liquid nitrogen to the reservoir. There is essentially no difference in the spectral sensitivity of the tube at low temperatures [10].

#### B. OPERATION OF THE SPECTROPHOTOMETER

The spectrophotometer is rolled into position opposite the port to be used in the Plasma Facility. The unit is raised and leveled so that the input optics are positioned as required [1]. The power switch of the Eldorado Unit is activated and one liter of liquid nitrogen is placed in the cooling reservoir. The variac is turned on and adjusted to heat

the output lenses. After fifteen minutes have elapsed, another liter of liquid nitrogen is added. It takes 30 minutes for the electronic equipment to settle out and after that interval the high voltage switch is activated. A lens cover is placed over the input optics and the meters for both photomultipliers are calibrated [14]. After removal of the lens cover, data may be taken.

The first line of interest is selected by use of the digital counters and the input optics are adjusted to give maximum intensity. The "B" channel photomultiplier intensity reading is used as the base intensity in all cases, and the "A" channel intensity reading is adjusted to equal "B". The method known as "leap-frogging" was used exclusively in this investigation, i.e., starting with the same line on each channel, with equal intensity on both, and moving on to the next, registering equal intensities on both channels before moving on to the next [1]. Thus all intensities end up being referenced to the first line to come under investigation. In this investigation, it was always the longest wavelength under study.

#### C. EXPERIMENTAL DATA AND COMPUTATIONS

A nitrogen plasma column is established at the Plasma Facility and the parameters of the system, magnetic field, arc current, arc pressure, and anode voltage are recorded. The magnetic field desired is selected and held constant while all the selected nitrogen lines are investigated. It takes approximately 30 minutes to evaluate 14 lines. The magnetic field is then changed and the parameters are checked for deviation. This is continued until all the lines have been evaluated at every magnetic field in question. For this investigation, the magnetic field was set at 2400, 3000, 3600, 4200, and 4800 gauss. The arc current was



constant at 60 amps and the anode voltage varied from 64 to 75 volts during separate runs. The arc pressure varied during any particular run from  $1.6 \times 10^{-4}$  to  $7.6 \times 10^{-5}$  torr. This will account for some variance in the results.

The intensities of each line are recorded as shown in Figure 6, and the uncorrected relative intensities (URI) are computed. The URI of line 1 is the reading for line 1, as both channels have been balanced with channel "B" being the base. The URI for the remaining lines is computed as follows: The URI of line 2 is to the URI of line 1 as the average reading for line 2 is to the reading of channel "B" (base channel) for line 1. Any changes in readings for the same line on two channels (caused by moving the gratings) must be taken into account, and thus the use of the average reading for line 2 above. The computations are continued substituting line 2 for line 1 and line 3 for line 2 proceeding through the remainder of the lines in the same manner. The URI must then be corrected for spectral sensitivity of the photomultiplier tubes used. (See Figure 7). The URI multiplied by the correction factor gives the Corrected Relative Intensity [1].

A computer program was written to calculate the temperature equation given in the "Spectroscopic Diagnostics" portion of this paper. However, before temperatures could be computed, the values of the maximum and minimum intensity ratios, the maximum wavelength separation, and the minimum excitation potential difference had to be determined. The program was adjusted so that one parameter could be varied while holding the others constant, and was broad enough so that the parameter varied could assume all values in question during one run of the computer. Limits on the values of parameters were established so that consistent

PLASMA SPECTROPHOTOMETER SAMPLE DATA

CHANNEL "A"

CHANNEL "B"

WAVE- LENGTH APPROX.	Ionic SPECIES	APPROX. SETTING	READING X 10 X RANGE	APPROX. SETTING	READING X 10 X RANGE	I (REL) UNCORR- ECTED	I (REL) CORR- ECTED
4643 A	N +	221.73	73	207.27	73	73	62.78
4621 "	"	220.45	54	206.05	49.5	51.75	44.51
4613 "	"	219.97	36	205.52	39	39.20	33.71
4607 "	"	219.58	60	205.14	56	58.30	50.14
4601 "	"	219.25	65	204.77	90	80.69	69.39
4535 "	N++	215.10	21.5	200.73	19.5	18.38	16.63
4518 "	"	214.19	55	199.73	49	49.01	44.35
4514 "	"	213.96	10.5	199.56	13	11.75	10.63
4200 "	"	196.02	200	181.43	125	146.91	143.24
4145 "	N +	193.02	22	178.43	21	37.68	37.11
4133 "	"	192.31	21	177.70	20	37.78	36.23
4124 "	"	191.83	12.5	177.14	13	23.45	23.10
4103 "	N++	190.67	6.7	176.00	7.5	12.81	12.62
4097 "	"	190.26	9.3	175.64	7.4	14.22	14.15

BY: J R C

PURPOSE: TEMP/DENSITY CALCULATION DATA

MAGNETIC FIELD: 3600 GAUSS

ARC CURRENT: 60 AMPS

ANODE VOLTAGE: 75 VOLTS

ARC PRESSURE: 1.6 X 10<sup>-4</sup> TORR

VIEW PORT: # 2

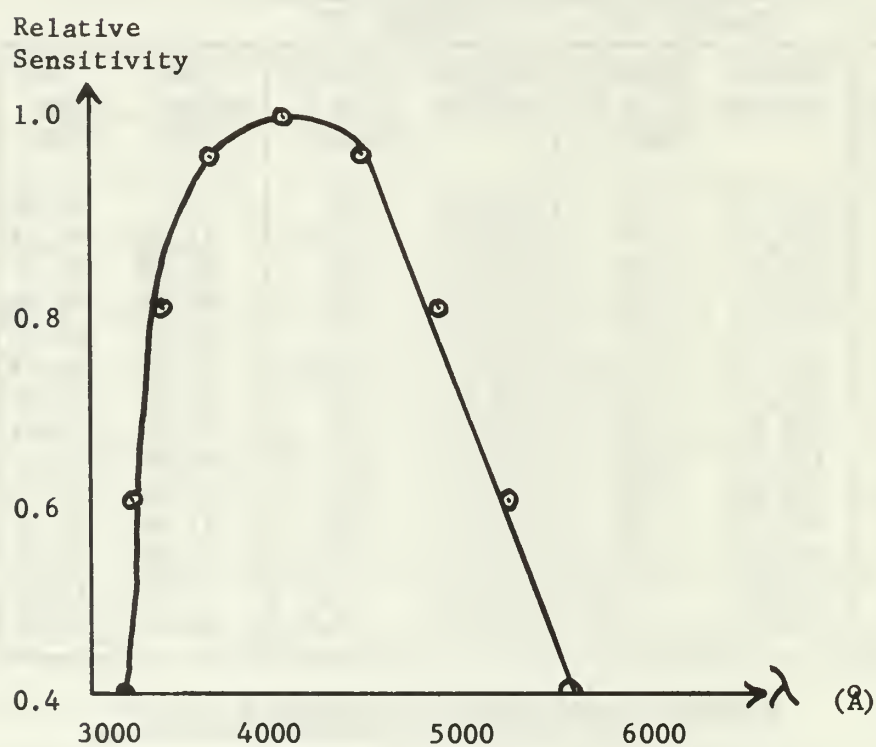
POSITION: Centered on Beam

RELATIVE INTENSITY CALCULATION TECHNIQUE: Leap - Frog All Referenced  
to Channel "B"

Figure 6

# 1P21 SPECTRAL SENSITIVITY AND RESULTANT CORRECTION FACTORS

## 1P21 SPECTRAL SENSITIVITY CURVE



## NET RELATIVE INTENSITY CORRECTION FACTORS

<u>Wavelength Range</u>	<u>Correction Factor</u>	<u>Deviation</u>
4000-4100 Å	0.995	0.005
4100-4200 "	0.985	0.005
4200-4300 "	0.975	0.005
4300-4400 "	0.965	0.005
4400-4500 "	0.945	0.015
4500-4600 "	0.905	0.025
4600-4700 "	0.860	0.020
4700-4800 "	0.805	0.025
4800-4900 "	0.765	0.025
4900-5000 "	0.720	0.020

Figure 7



values of temperature were obtained. Three different sets of relative intensities determined on three separate runs of the Plasma Facility were used to keep the diagnosis unbiased. Limits established for the parameters were maximum relative intensity of 4.0, minimum relative intensity ratio of 0.25, maximum wavelength separation of 500 angstroms, and minimum excitation potential difference of 7.0 volts. The computer program with all corrections included and all parametric varying devices removed is shown on page 36.

A computer program to calculate relative number density ratios of the two nitrogen species was written and modified with the inclusion of the above determined parameters [1], and is shown on page 39. The temperature used in this computation must be taken from the temperature calculation above and entered as a constant. The average temperature is usually chosen, however any temperature within the standard deviation of the mean will suffice.

#### IV. RESULTS AND CONCLUSIONS

##### A. RESULTS

##### 1. Electron Temperatures

Entering data similar to that shown in Figure 6 into the electron temperature program led to quantitative results for the electron temperature. The local electron temperature was found to vary with increasing magnetic field and is shown in Figure 8 for the case of the singly ionized nitrogen atom.

The temperature varied from 3.85 electron volts at 2400 gauss to a peak temperature of 8.1 electron volts at 4200 gauss. It dropped rapidly to 4.4 electron volts at 4800 gauss. The compression of the plasma column into a smaller volume as the magnetic field is increased can be physically observed from the side of the Plasma Facility. The density of the singly ionized atoms must then increase and consequently atomic interactions increase giving rise to higher temperatures. Above 4200 gauss, the electron temperature decreases rapidly plausibly due to the collision rate increasing at such a rate as to cause a corresponding decrease in diffusion rate, and thus a greater distribution of energy throughout the column. These temperatures, Figure 8, closely approximate those found by Major Thomas J. Haycraft, USA, whose studies of the plasma column under the same conditions were conducted using probe techniques and frequency analyses.

The temperatures determined for the doubly ionized nitrogen atom were not usable as they were consistently unrealistic and irregular. Temperatures varied from 10 electron volts to 237 electron volts, well above arcing potential. Evaluation of individual

# ELECTRON TEMPERATURE VS MAGNETIC FIELD

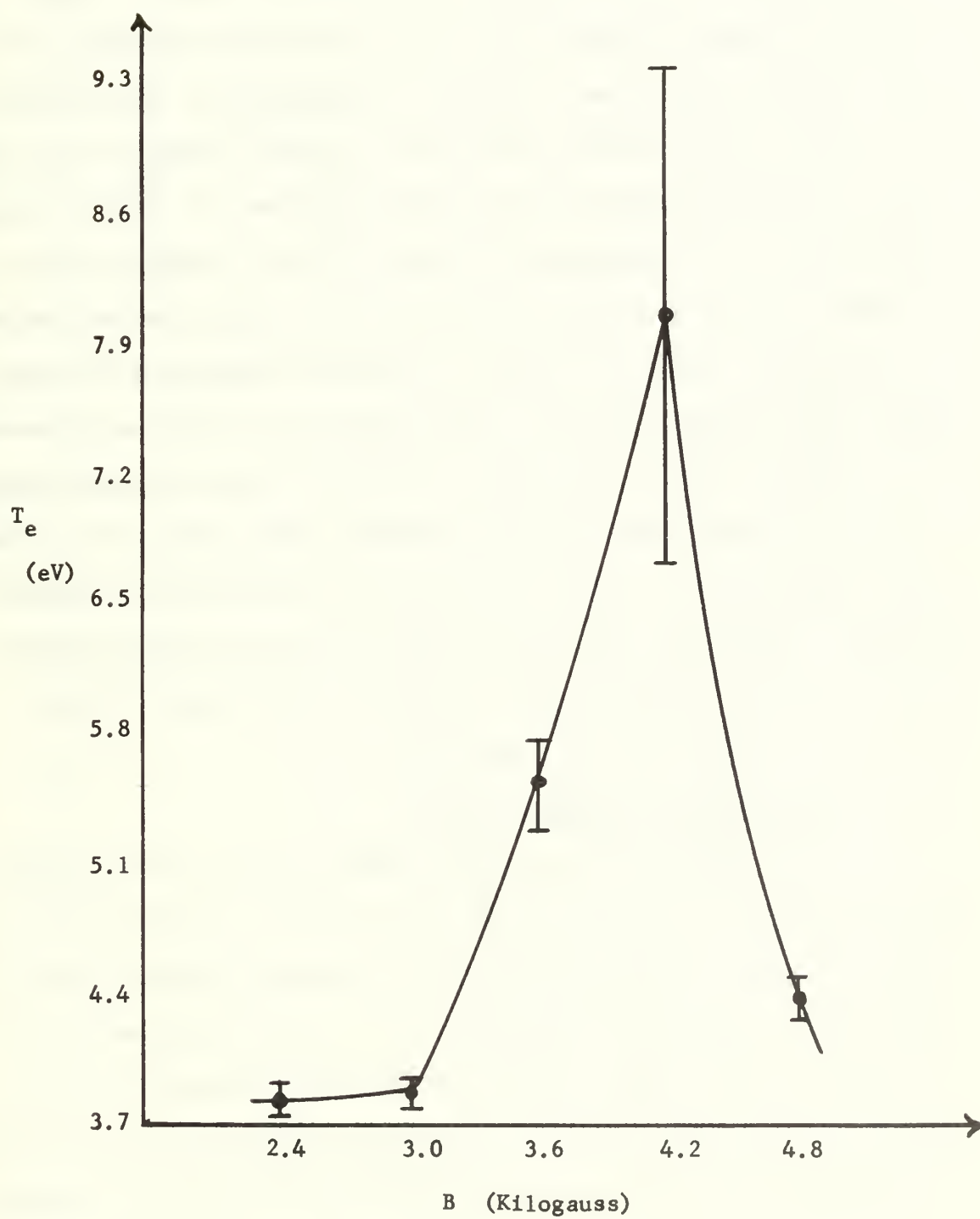


Figure 8

temperatures showed that out of six temperatures determined for each machine run at constant magnetic field, four were negative temperatures. Investigation of the lines giving these data showed that each was an allowed transition, and that two of the lines are noted as among the more intense nitrogen lines. Improper identification of lines is not the problem, as in each case, there are no nitrogen lines or argon lines which could be misconstrued as the identified lines [4]. Their relative intensities are not consistent with those relative intensities shown in Table II, but the relative intensities of the singly ionized species are consistent. There is no readily acceptable explanation for these deviations because the relative intensities for all lines are determined in a single run with a single base. As for the negative temperatures, it seems to follow that the doubly ionized nitrogen atom is not in local thermal equilibrium, and that the velocity of the electrons is not Maxwellian. The electron density is probably such that radiative depopulation of lower energy states is prevalent, giving higher electron temperatures than the actual temperature.

## 2. Relative Number Density, $N_{++}/N_{+}$

It was necessary following the results of the electron temperature calculations to assume that the local electron temperature for the singly ionized nitrogen atom was the local electron temperature for the system for the purpose of obtaining relative number densities of the two species studied. The average local electron temperature for the singly ionized nitrogen atom for a particular magnetic field was entered as a constant in the relative number density program, and the corresponding computational data were entered and the program run. The data and the temperature were changed for each value of magnetic field studied

# RELATIVE NUMBER DENSITY VS

MAGNETIC FIELD

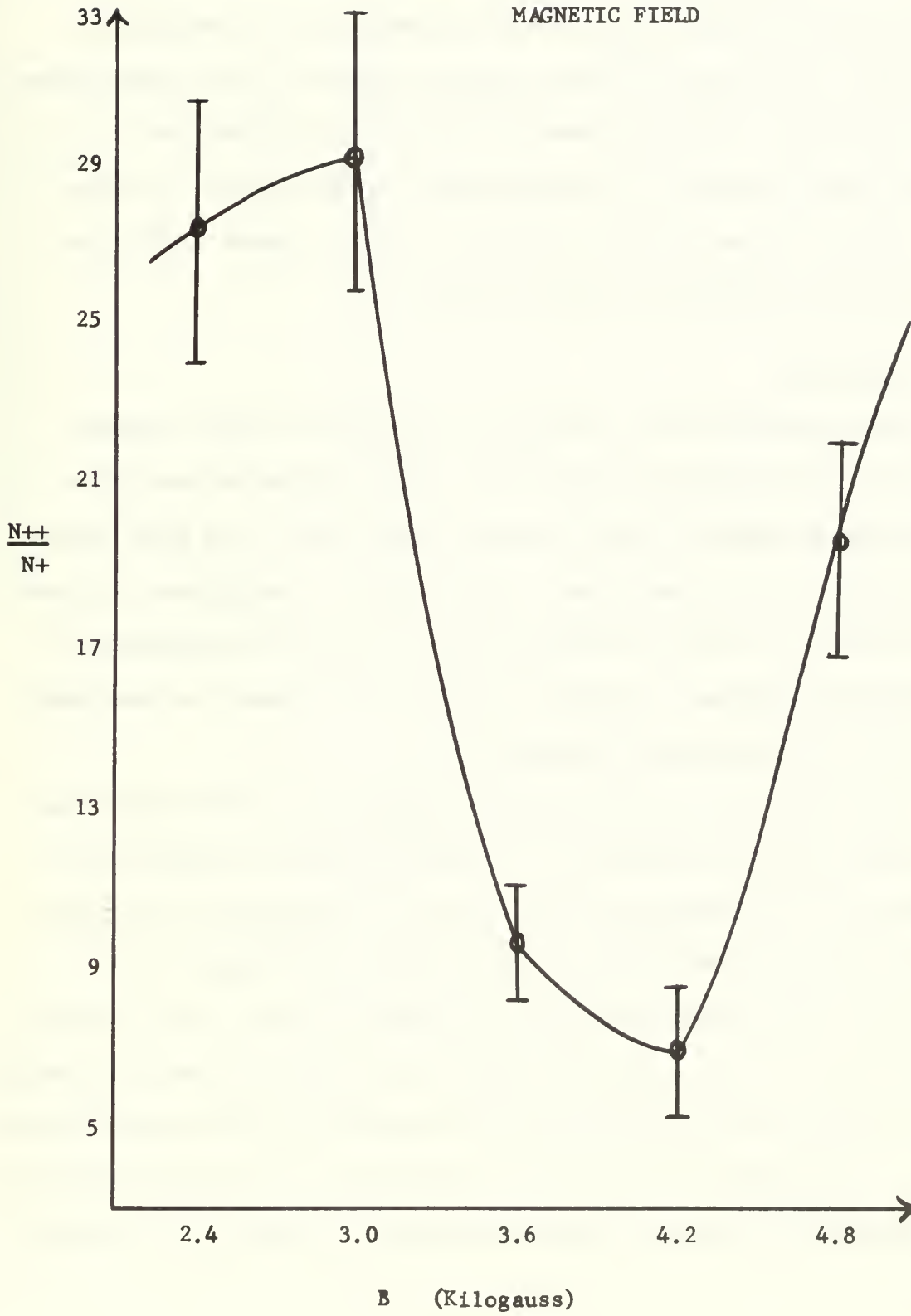


Figure 9



(See Figure 9). As the magnetic field increased to 4200 gauss, the relative number density decreased in accordance with the postulated increase in the density of the singly ionized atom. The density of the doubly ionized atom must also decrease somewhat, as the temperatures calculated show an approach towards the local equilibrium state, i.e., from 48 electron volts to 18 electron volts at 3600 gauss. This does not in any way assume that the condition of local thermal equilibrium is achieved by the doubly ionized nitrogen atom.

## B. CONCLUSIONS

This investigation has identified the variance in local electron temperature with magnetic field for the singly ionized nitrogen atom and determined that the singly ionized nitrogen atom is in local thermal equilibrium in the plasma column. The variance in temperature with magnetic field of the doubly ionized nitrogen atom was not determined to a satisfactory degree. The doubly ionized nitrogen atom was determined not to be in local thermal equilibrium.

It was shown that the local electron temperature of the system was the local electron temperature of the singly ionized nitrogen atom as evidenced by the comparison of local electron temperatures to relative number densities determined at the same temperature (Figure 10).

As the "theta pinch" device became operational late in the investigative period, and still requires further modification, it was not possible to include an analysis of shock wave perturbations on the nitrogen plasma column. It is felt that this can be accomplished in the future utilizing the equipment, as modified, and the procedures developed in this investigation.

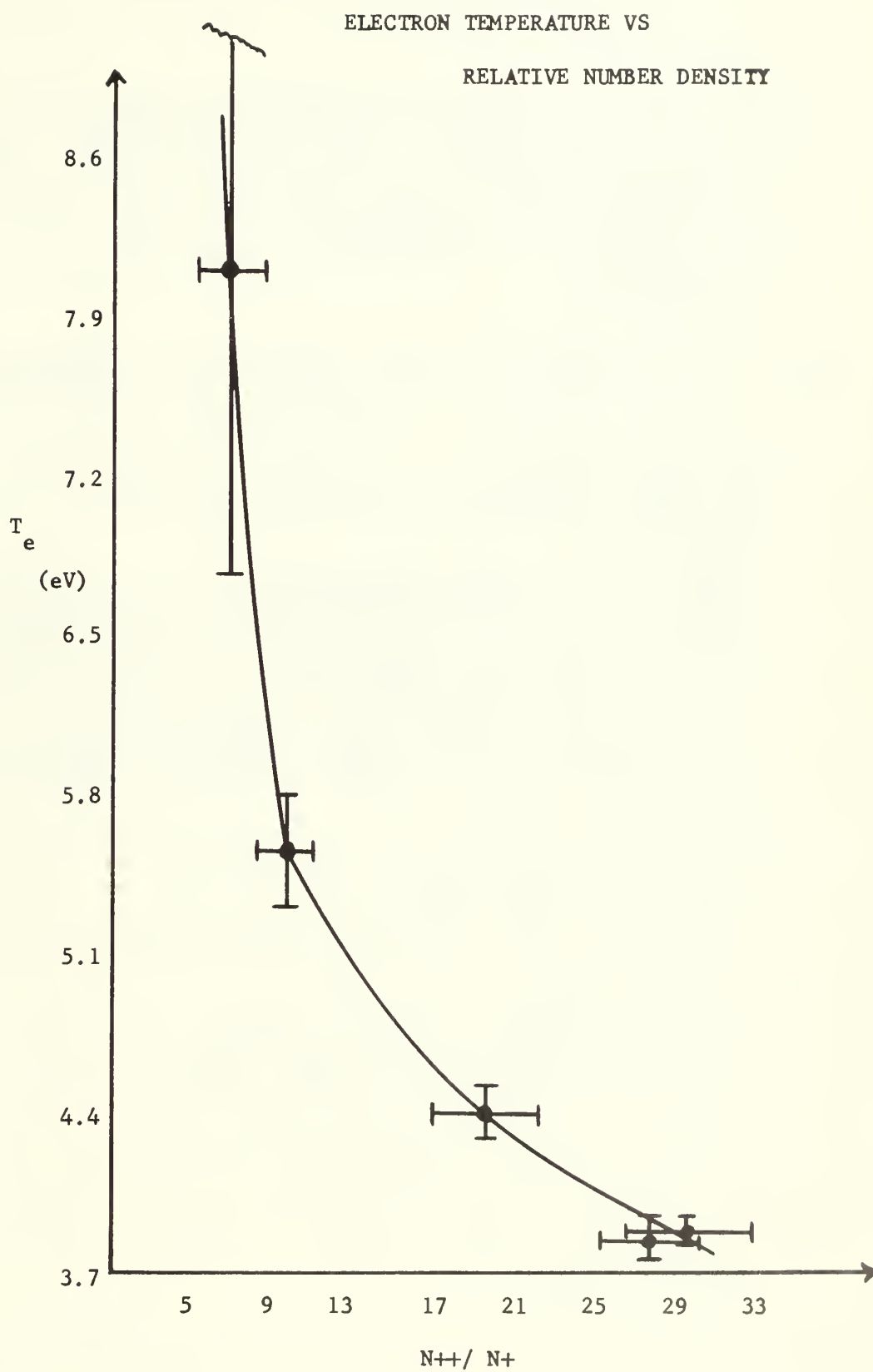


Figure 10

# ELECTRON TEMPERATURE COMPUTER PROGRAM

THIS PROGRAM CALCULATES PLASMA ELECTRON TEMPERATURES FROM INTENSITY RATIOS (GAINED BY PHOTOELECTRIC MEANS) OF SELECTED SPECTRAL LINES AND THEIR CHARACTERISTIC DATA, AND THEN, TAKES THESE TEMPERATURES AND CALCULATES THEIR MEAN, VARIANCE, AND STANDARD DEVIATION.

```

DIMENSION GLOW(50),F(50),EXCIPC(50),RELINT(50),WL(50)
1JLOW(50),JUPPER(50),TEMP(500),RATIC(500)
DIMENSION ARMAX(15),ARMIN(15)
REAL GLOW,F,EXCIPC,RELINT,WL,B,TEMP,EVCCNV,RATIO,JLOW,
1N,JUPPER,KRIS
INTEGER S,Z
VWL=500.E-10
VF=7.0

```

THE ABOVE CARDS WILL PRINT OUT THE WAVELENGTH MAXIMUM AND EXCITATION POTENTIAL MINIMUM DIFFERENCES USED IN THE CALCULATIONS. THEY SHOULD BE CHANGED EVERY TIME THOSE DIFFERENCES ARE CHANGED IN THE BODY OF THE PROGRAM.

```

ARMAX(1)=6.0
ARMIN(1)=1.0/6.0

```

THE ABOVE CARDS SET A MAX AND A MIN ON THE THE RELATIVE INTENSITY RATIO OF ANY TWO (2) SPECTRAL LINES.

```

EVCCNV=1.60207E-19
B=1.38042E-23

```

```

1  FFORMAT (15)
2  FFORMAT (4F10.0,E13.0,7X,F10.0)
3  FFORMAT ('1',5X,'NC.',4X,'WAVELENGTH',7X,'EXCITATION
1POTENTIAL',11X,'J',17X,'J',11X,'ABSCRIPTION',4X,
2'RELATIVE',5X,'2J+1',/14X,'(METERS)',15X,'(VCLTS)',,
311X,'(UPPER LEVEL)',5X,'(LOWER LEVEL)',6X,'STRENGTH',
45X,'INTENSITY',4X,'(LCW)')///)
4  FFORMAT(/,5X,F4.0,2X,4PE13.3,12X,OPF7.3,17X,F3.1,15X,
1F3.1,11X,F8.5,6X,F7.2,5X,F4.1)
5  FFORMAT ('1',5X,'NC.',5X,'E-TEMPERATURE',5X,
1'WAVELENGTH(1)',5X,'WAVELENGTH(2)',5X,'INTENSITY RATIO
2'/13X,'(DEGREES KELVIN)',7X,'(METERS)',10X,'(METEPS)'
3///)
6  FFORMAT (5X,F4.0,6X,1PE11.4,7X,4PE13.3,5X,4PE13.3,8X,
11PE11.4/)
10 FFORMAT (/////////25X,'E-TEMPERATURE = ',1PE11.4,2X,
1'+/-',2X,OPF11.4,2X,'DEGREES KELVIN',2X,'*****')
11 FFORMAT (20X,4PE13.3/)
12 FFORMAT ('1',18X,'WAVELENGTHS CHECK'////////)
14 FFORMAT (////////15X,'THE TCTAL NUMBER OF ACCEPTABLE
1COMPUTATIONS (I.E.,WITHIN SPECIFIED LIMITS) MADE= ',
2F5.0)
200 FFORMAT('1',14X,'MAXIMUM WAVELENGTH DIFFERENCE = ',3PE1
10.1,2X,'METERS')
201 FFORMAT(////////15X,'MINIMUM EXCITATION POTENTIAL
1DIFFERENCE = ',F4.1,2X,'VOLTS'////////)
202 FFORMAT (15X,'MAXIMUM ALLOWABLE INTENSITY RATIO = ',
1F6.1////////15X,'MINIMUM ALLOWABLE INTENSITY RATIO = ',
2F5.2///)
205 FFORMAT (////////25X,'E-TEMPERATURE = ',F7.4,2X,'+/-',2X,
1F7.4,2X,'ELECTRON VCLTS',2X,'*****')
210 FFORMAT(/35X,'TEMPERATURE RANGE: ',2X,1PE11.4,2X,'TO',
12X,1PE11.4)
211 FFORMAT (/35X,'TEMPERATURE RANGE: ',2X,F7.4,2X,'TO',
12X,F7.4)
212 FFORMAT(/35X,'PERCENT ERROR = ',2X,F7.2,2X,'PERCENT')
2C  READ (5,1) J
WRITE (6,12)
IF (J) 100,100,21
21 DO 80 I=1,J

```

THE ABOVE DO LOOP CHECKS TO SEE IF ALL DATA HAS BEEN ENTERED



```

      READ (5,2) EXCIP0(I),JUPPER(I),JLCW(I),F(I),WL(I),
      1RELINT(I)
      WRITE(6,11) WL(I)
8C CONTINUE
THE ABOVE INSTRUCTION WILL READ DATA ON A SERIES OF "J"
SPECTRAL LINES.
      N=1.0
      WRITE (6,3)
      DC 22 I=1,J
      GLCW(I)=(2.0*JLCW(I))+1.0
      WRITE (6,4) N,WL(I),EXCIP0(I),JUPPER(I),JLCW(I),F(I),
      1RELINT(I),GLOW(I)
      N=N+1.0
22 CONTINUE
      DC 502 Z=1,3
      ARMAX(Z+1)=ARMAX(Z)-1.0
      ARMIN(Z)=1.0/ARMAX(Z+1)
      RATMAX=ARMAX(Z+1)
      RATMIN=ARMIN(Z)
      N=1.0
      S=1
      WRITE (6,5)
      DC 26 I=1,J
      DC 66 MAP=I,J
      KRIS=EXCIP0(MAP)-EXCIP0(I)
      CHECK=ABS(KRIS)
      IF (CHECK.LT.VE)GC TC 70
THE ABOVE INSTRUCTION CHECKS TO SEE IF THE DIFFERENCE IN EX-
CITATION POTENTIAL IS GREATER THAN 7.0 ELECTRON VOLTS. THE
DIFFERENCE MUST BE SEVERAL VOLTS FOR VALID RESULTS.
      WAVE=ABS(WL(I)-WL(MAP))
      IF (WAVE.GT.VWL)GC TC 70
THE ABOVE INSTRUCTION CHECKS TO SEE IF THE DIFFERENCE IN
WAVELENGTHS IS LESS THAN 500 ANGSTROMS. MUST BE FOR VALID
RESULTS.
      IF (KRIS) 24,100,23
23 RATIO(S)=RELINT(I)/RELINT(MAP)
      VANG=RATIO(S)
      IF (VANG.GT.RATMAX)GC TC 70
      IF (VANG.LT.RATMIN)GC TC 70
      TEMP(S)=(((EXCIP0(MAP)-EXCIP0(I))*(EVCONV))/B)/ALOG
      1((RATIO(S))*(GLCW(MAP)/GLOW(I))*(F(MAP)/F(I))*(WL(I)**
      23.0/WL(MAP)**3.0))
      GO TO 25
24 RATIO(S)=RELINT(MAP)/RELINT(I)
      VUNG=RATIO(S)
      IF (VUNG.GT.RATMAX)GC TC 70
      IF (VUNG.LT.RATMIN)GC TC 70
      TEMP(S)=(((EXCIP0(I)-EXCIP0(MAP))*(EVCONV))/B)/ALOG
      1((RATIO(S))*(GLCW(I)/GLCW(MAP))*(F(I)/F(MAP))*(WL(MAP)
      2*3.0/WL(I)**3.0))
      GO TO 25
7C TEMP(S)=0.0
      RATIO(S)=0.0
THIS PROGRAM IS SET UP TO RECORD A VALUE OF 0.0 FOR TEMPERA-
TURE AND RATIO IF THE EXCITATION POTENTIAL DIFFERENCE OR
WAVELENGTH DIFFERENCE DO NOT MEET ABOVE CRITERIA. IT WILL
ALSO ADJUST THE VALUE OF N FOR THE COMPUTATION OF THE MEAN,
ETC.
25 WRITE (6,6) N,TEMP(S),WL(I),WL(MAP),RATIO(S)
      N=N+1.0
      S=S+1
66 CONTINUE
26 CONTINUE
      SUM=0.0
      ASUM=0.0
      N=N-1
      S=S-1
      DC 27 I=1,S
      TEMP(I)=ABS(TEMP(I))
      IF (TEMP(I).EQ.0.0)N=N-1.0
27 SUM=SUM+TEMP(I)

```



# RELATIVE NUMBER DENSITY COMPUTER PROGRAM

THIS PROGRAM CALCULATES THE RELATIVE NUMBER DENSITIES OF TWO SPECIES IN A PLASMA FROM THEIR SPECTRAL LINE DATA. THE TWO SPECIES ARE CALLED N1 AND N2, WITH THE N2 SPECIES HAVING THE HIGHER EXCITATION POTENTIAL (IN GENERAL) AND BEING ENTERED AS THE SECOND OF TWO DATA SETS.

```
DIMENSION GLOW(4,50),F(4,50),EXCIPQ(4,50),RELINT(4,50)
1WL(4,50),JLOW(4,50),JUPPER(4,50),RATIO(50,50),
2NUMDEN(50,50)
REAL GLOW,F,EXCIPC,RELINT,B,WL,TEMP,EVCONV,RATIO,JLOW,
1JUPPER,KRIS,NONE,NTWO,NUMDEN,N,MATE
EVCONV=1.30207E-19
B=1.38042E-23
VWL=500.F-10
VE=7.0
```

THE ABOVE 2 CARDS GIVE THE MAXIMUM WAVELENGTH AND MINIMUM EXCITATION POTENTIAL DIFFERENCES USED IN THE COMPUTATIONS.

```
RATMAX=4.0
RATMIN=0.25
```

THE TWO CARDS ABOVE SET A MAX AND A MIN ON THE RELATIVE INTENSITY RATIO OF ANY TWO SPECTRAL LINES.

```
TEMP=44700.0
```

TEMPERATURE IS CONSIDERED A CONSTANT FOR THESE CALCULATIONS. THE VALUE OF TEMPERATURE USED SHOULD BE OBTAINED FROM THE ELECTRON TEMPERATURE COMPUTER PROGRAM FOR THE SPECTRAL DATA USED HEREIN.

```
1 FORMAT('1',9X,'ELECTRON TEMPERATURE = ',F9.0,2X,
1'DEGREES KELVIN')
2 FORMAT (I5)
3 FORMAT ('1',20X,'DATA CHECKS'////////)
4 FORMAT (4F10.0,E13.0,7X,F10.0)
5 FORMAT (20X,4PE13.3/)
6 FORMAT ('1',3X,'NO.',5X,'WAVELENGTH',7X,'EXCITATION
1POTENTIAL',11X,'J',17X,'J',11X,'ABSORPTION',4X,
2'RELATIVE',5X,'2J+1'/13X,'(METERS)',15X,'(VCLTS)',11X,
3'(UPPER LEVEL)',5X,'(LOWER LEVEL)',6X,'STRENGTH',5X,
4'INTENSITY',4X,'(LCW)'////)
7 FORMAT (1X,F4.0,F4.0,1X,4PE13.3,12X,OPF7.3,16X,F4.1,
114X,F4.1,10X,F8.5,6X,F7.2,5X,F4.1/)
8 FORMAT ('1',4X,'N2.',3X,'WAVELENGTH(2)',5X,'N1.',3X,
1'WAVELENGTH(1)',10X,'INTENSITY RATIO',11X,'NUMBER
2DENSITY RATIOS'/13X,'(METERS)',16X,'(METERS)',15X,
3'(I(2)/I(1))',19X,'N(2)/N(1)'////)
9 FORMAT (/4X,F4.0,3X,4PE13.3,4X,OPF4.0,3X,4PE13.3,12X,
11PE10.3,20X,2PE10.2)
10 FORMAT ('1',14X,'SUM = ',4PE12.2,///15X,'AVERAGE
1NUMBER DENSITY RATIO = ',2PE10.2/////15X,'ABS(NBAR-N)
2',15X,'ABS((NBAR-N)SQ)')
11 FORMAT (/15X,2PE10.2,18X,2PE10.2)
12 FORMAT ('1',14X,'THE TOTAL NUMBER OF ACCEPTABLE
1COMPUTATIONS (I.E.,WITHIN SPECIFIED LIMITS) MADE = ',
2F5.0)
13 FORMAT(///15X,'STANDARD DEVIATION = ',12X,E10.4//15X
1,'STANDARD DEVIATION OF THE MEAN = ',E10.4)
14 FORMAT (//////////20X,'THE NUMBER DENSITY RATIO OF
1SPECIES 2 TO SPECIES 1 = ',2PE10.2,2X,'+/-',1X,OPF8.2
2,'*****')
200 FORMAT (////////10X,'MAXIMUM WAVELENGTH DIFFERENCE = ',
13PE10.1,2X,'METERS')
201 FORMAT (////////10X,'MINIMUM EXCITATION POTENTIAL
1DIFFERENCE = ',F4.1,2X,'VCLTS'////////)
202 FORMAT (10X,'MAXIMUM ALLOWABLE INTENSITY RATIO = ',
1F6.1////////10X,'MINIMUM ALLOWABLE INTENSITY RATIO = ',
2F5.2////)
```

SPECIES 2 = N++, AND SPECIES 1 = N+ FOR THIS INVESTIGATION.

```

500 READ (5,2) INDIA
    IF (INDIA) 501,501,502
502 WRITE (6,3)
    DO 30 I=1,INDIA
        READ (5,4) EXCIP0(1,I),JUPPER(1,I),JLCW(1,I),F(1,I),
        1WL(1,I),RELINT(1,I)
    THE ABOVE CARD WILL READ THE N1 DATA SET CONSISTING OF A
    TCTAL OF "INDIA" NUMBER OF CARDS.
        WRITE (6,5) WL(1,I)
    THIS PRINT-OUT CHECKS TO SEE THAT ALL DATA IS ENTERED.
    30 CONTINUE
        READ (5,2) JULIFT
        WRITE (6,3)
        DO 31 I=1,JULIFT
            READ (5,4) EXCIP0(2,I),JUPPER(2,I),JLOW(2,I),F(2,I),
            1WL(2,I),RELINT(2,I)
    THE ABOVE CARD WILL READ THE N2 DATA SET CONSISTING OF A
    TCTAL OF "JULIFT" NUMBER OF CARDS.
        WRITE (6,5) WL(2,I)
    THIS PRINT-OUT CHECKS TO SEE THAT ALL DATA IS ENTERED.
    31 CONTINUE
        NCNE=1.0
        NTWO=1.0
        WRITE (6,6)
        KILC=INDIA
        DO 33 K=1,2
        DO 32 I=1,KILC
            GLCW(K,I)=(2.0*JLCW(K,I))+1.0
            WRITE (6,7) NONE,NTWC,WL(K,I),EXCIP0(K,I),JUPPER(K,I),
            1JLOW(K,I),F(K,I),RELINT(K,I),GLCW(K,I)
    FOR THE RESULTING PRINT-OUT, THE FIRST NUMBER WILL INDICATE
    THE DATA SET AND THE SECCND WHICH ONE OF THAT DATA SET.
        NTWO=NTWO+1.0
    32 CONTINUE
        NCNE=NONE+1.0
        NTWC=1.0
        KILO=JULIFT
    33 CONTINUE
        NONE=1.0
        NTWO=1.0
        WRITE (6,8)
        DO 39 K=1,JULIFT
        DO 38 I=1,INDIA
            KRIS=EXCIP0(2,K)-EXCIP0(1,I)
            CHECK=ABS(KRIS)
            IF (CHECK.LT.VE)GC TC 34
    THIS INSURES THAT THE DIFFERENCE IN EXCITATION PCTENTIALS IS
    GREATER THAN OR EQUAL TO 7.0 VOLTS WHICH IS NECESSARY FOR
    VALID RESULTS.
            MATE=ABS(WL(2,K)-WL(1,I))
            IF (MATE.GT.VWL)GC TC 34
    THIS INSURES THAT THE DIFFERENCE IN WAVELENGTHS IS EQUAL TO
    OR LESS THAN 500 ANGSTROMS. NECESSARY FOR VALID RESULTS.
            RATIO(K,I)=RELINT(2,K)/RELINT(1,I)
            VCNG=RATIO(K,I)
            IF (VCNG.GT.RATMAX)GC TC 34
            IF (VONG.LT.RATMIN)GC TC 34
            NUMDEN(K,I)=(RATIO(K,I)*(GLOW(1,I)/GLOW(2,K)))*(F(1,I)/
            1F(2,K))*((WL(2,K)/WL(1,I))*3.0)*(EXP((KRIS*EVCONV)/
            2(B*TEMP))))
            GC TC 35
    34 NUMDEN(K,I)=0.0
        RATIO(K,I)=0.0
    IF THE EXCITATION POTENTIAL DIFFERENCE OR WAVELENGTH DIFFER-
    ENCE DO NOT MEET ABOVE CRITERIA, THE VALUES OF THE NUMBER
    DENSITY RATIO AND THE INTENSITY RATIO WILL BE SET TO ZERO.
    35 WRITE (6,9)NTWC,WL(2,K),NONE,WL(1,I),RATIO(K,I),
        1NUMDEN(K,I)
        NCNE=NONE+1.0
        XPAY=NONE
    38 CONTINUE
        NTWO=NTWO+1.0

```





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<div>14</div> <div>KEY WORDS</div>	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Plasma Spectrophotometer Nitrogen Plasma Local Electron Temperature						













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